Fyz. čas. SAV 21 (1971), No. 2-3

MAGNETIC FIELD DEPENDENCE OF ACOUSTOELECTRIC CURRENT IN INDIUM ANTIMONIDE

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The experimental dependences of the current density decrease $\Delta i(B)$ from the initial value i_0 on the transverse magnetic field after the acoustoelectric domain formation in n-InSb are given for various constant current densities i_0. The current decrease is identified as an acoustoelectric current, which corresponds to the optimally amplified thermal acoustic wave and the formula is derived, which fits well the experimental dependences in not too strong external electric and magnetic fields. Also the ratio of the lattice attenuation to the attenuation on conduction electrons in the absence of external fields for the wave of the optimally amplified frequency is given.

Investigating the acoustoelectric domains in n-InSb at 77 °K, we have measured the dependence of the current decrease ΔI after the domain formation from its initial constant value I_0 on the transverse magnetic field. The pulse duration was 10 μs and the repetition frequency 10 Hz. The sample was a prisma of the dimensions $19 \times 1.7 \times 0.75$ mm^3 with longitudinal axes oriented in the $\langle 110 \rangle$ direction. Electron concentration and mobility measured in the range of low fields and at 77 °K had the following values: $n = 6 \times 10^{20}$m^{-3}, $\mu_0 = 27$ m^2/Vs. The current I_0 and its decrease ΔI were measured on calibrated resistance by an oscilloscope. A typical oscillograph with denoted measured values is shown in Fig. 1.

In order to keep the current constant with the magnetic field varying, it was necessary to change the electric field strength according to the dependence

$$E = E_0 \left(1 + \frac{bB^2}{1 + cB}\right), \qquad (1)$$

where the parameters b and c are independent from the magnetic field B. We have confirmed the dependence of this type by a series of measurements in the range of low (of the order of 10^{-3} V/cm) as well as in the range of strong

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(of the order of 10 V/cm) electric fields. From this dependence the empirical formula for the electron mobility follows

$$\mu = \mu_0 \left(1 + \frac{bB^2}{1 + cB}\right)^{-1}, \quad (2)$$

which will be used later. We wish to mention that for the interpretation of the acoustic wave amplifications in n-InSb in a transverse magnetic field at 77 °K Hyakawa and Kikuchi [1] used, to express the mobility in an alternating electric field — corresponding to the acoustic field — the formula of the type

$$\mu = \mu_0(1 + bB^2)^{-1} \quad (3)$$

and for the mobility in the external constant field they used the formula

$$\mu = \mu_0(1 + aB)^{-1}. \quad (4)$$

However, in paper [2] the same authors mentioned that a better agreement with the experiment can be reached by the use of the dependence

$$\mu = \mu_0 \,[1 + (\mu_0 B)^{1.2-1.3}]^{-1} \quad (5)$$

instead of (3) for the a. c. mobility in the formula for amplification. The suggested formula (2) passes into formula (3) for $cB \ll 1$ and becomes one of the type (4) for $cB \gg 1$. It is also evident that in a certain range of the magnetic field it can be approximated by the relation (5). An exact theoretical approach leads to rather complicated integrals, especially in the range of magnetic fields for which the relation $\mu_0 B \approx 1$ holds, which is our case. For this reason a simple empirical formula is advantageous.

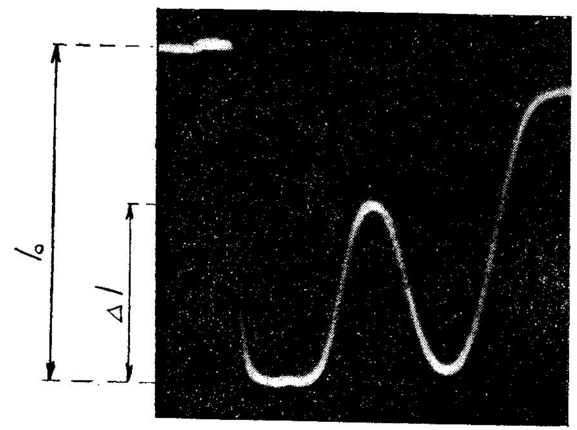

Fig. 1. A typical oscillograph of the current pulse with denoted measured values.

The dependence of the current density decrease Δi after the acoustoelectric domain formation on the magnetic field at the given initial current density i_0 higher than the threshold current density for the creation of domains is shown in Fig. 2.

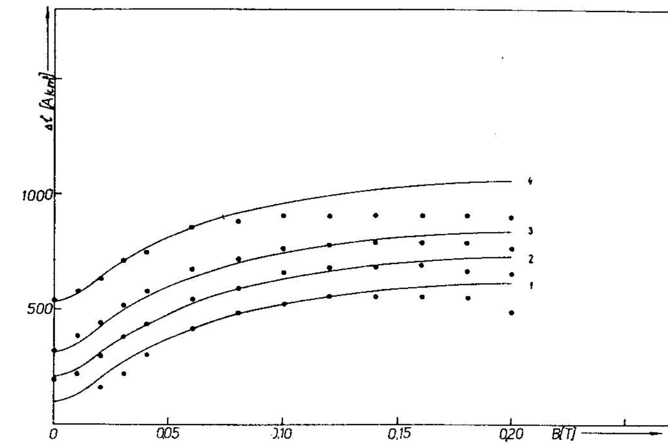

Fig. 2. The magnetic field dependence of the current decrease. Full circle denote the measured values, full lines are computed according to formula (9); 1 corresponds to the current density $i_0 = 767$ A cm^{-2}, 2 is for $i_0 = 878$ A cm^{-2}, 3 is for $i_0 = 988$ A cm^{-2}, and 4 is for $i_0 = 1207$ A cm^{-2}.

Interpreting this dependence we start from the concept that the current decrease corresponds to the acoustic flux of optimally amplified thermal acoustic waves propagating against the direction of electric field which is applied to the sample. For the amplification we use the well known White formula [3] which for the optimally amplified frequency $\omega_m = (\omega_c \omega_D)^{1/2}$ has the form

$$\alpha_e = \frac{K^2 \gamma \omega_c}{2 v_s (\gamma + 4\omega_c/\omega_D)}. \quad (6)$$

In this relation K^2 is an electromechanical coupling constant, $\omega_c = en\mu/\varepsilon$, $\omega_D = ev_s^2/\mu k_0 T$, e is an electronic charge, v_s is the velocity of fast shear waves in the $\langle 110 \rangle$ direction, ε is a dielectric permitivity, k_0 is the Boltzman constant and T is the temperature. The quantity $\gamma = v_d/v_s - 1$, where v_d is the electron drift velocity, can be rewritten in the form

$$\gamma = \frac{i_0 - \Delta i(B)}{env_s} - 1. \quad (7)$$

With an increasing acoustic flux also the current decrease increases until the amplification coefficient of the thermal acoustic wave on the conduction electrons reaches the value of the lattice attenuation α_L. When the sample is sufficiently long the current decrease at a given initial current density i_0 and a constant magnetic field will reach the maximum when the ralasion $\alpha_e = \alpha_L$ holds. This maximum value can be computed substituting into formula (6) α_L for α_e and using relation (7) for γ. In this way we get

$$\Delta i(B) = i_0 - env_s \left\{ 1 + \frac{K^2\omega_c}{4v_s\alpha_L} \left[1 - \left(1 - \frac{64v_s^2\alpha_L^2}{K^4\omega_c\omega_D} \right)^{1/2} \right] \right\}. \qquad (8)$$

Assuming that

$$\frac{64v_s^2\alpha_L^2}{K^2\omega_c\omega_D} \ll 1$$

the relation (8) can be simplified to

$$\Delta i(B) = i_0 - env_s \left(1 + \frac{\alpha_L}{\alpha_0} \frac{1}{1 + bB^2/(1 + cB)} \right) \qquad (9)$$

where for the electron mobility relation (2) was used and the symbol

$$\alpha_0 = \frac{K^2ev_s}{8\mu_0k_0T}$$

means the attenuation of the acoustic wave with the frequency $\omega_m = (\omega_c\omega_D)^{1/2}$ on the conduction electrons in the absence of outside fields.

The full lines in Fig. 2 are computed according to formula (9) with $n = 6.85 \times 10^{14}$ cm^{-3}, $v_0 = 2.28 \times 10^5$ cm s^{-1}, $b = 780$ T^{-2} $\sim \mu_0^2$, $c = 30$ T^{-1}, $\alpha_L/\alpha_0 = 26$.

It can be seen from Fig. 2 that formula (9) shows a good agreement with the experiment in not too high magnetic fields and that the higher the current density i_0 is the lower are the experimental values compared to the computed ones in weaker magnetic fields. In all cases the current decrease becomes lower than that given by formula (9) when the electric field exceeds approximately 55 V/cm and the deviations increase with an increasing electric field.

According to formula (9) at the given magnetic field Δi depends linearly on the current density provided that the electron concentration is constant. In Fig. 3 there is the Δi versus i dependence for $B = 0$, and in Fig. 4 there is a plot of i and $i - \Delta i$ versus E, respectively, for $B = 0$. From Fig. 4 is can be seen that the current density does not show a tendency for saturation, which may be interpreted in such a way that in the range of electric fields above 50 Vcm^{-1} the concentration of electrons increases. We have measured the dependence of the Hall voltage at a constant magnetic field $B = 0.2$ T on the electric field up to 100 V cm^{-1} and we have found the dependence of the electron concentration on the electric field, which is shown in Fig 5. However, this dependence can only partly explain the observed deflections of the measured values from those computed from formula (9). Other reasons, as, e. g. the nonlinear dependence of the acoustoelectric current on the acoustic flux as well the approximative character of White's formula and formula (2) used for the mobility of electrons, can also be responsible for the observed deviations.

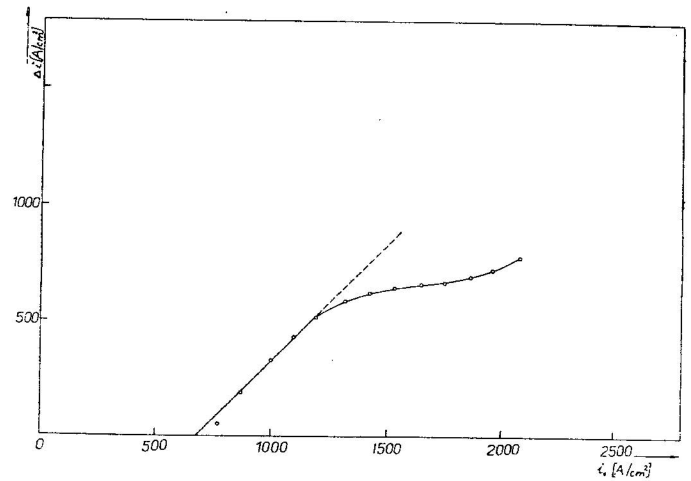

Fig. 3. Current decrease as a function of current density in the case $B = 0$.

Let us consider now the value of the ratio $\alpha_L/\alpha_0 = 26$ which we have used comparing the theory with the experiment. If we use for the piezoelectric constant $e_{14} = 0.071$ C m^{-2} [4], $\varrho = 5.8 \times 10^3$ kg m^{-3}, $v_s = 2.28 \times 10^3$ m s^{-1}, $\varepsilon = 17\varepsilon_0$, we obtain for $K^2 = 1.11 \times 10^{-3}$. Then from (10) we get $\alpha_0 = 0.15$ dB cm^{-1}, so that α_L for the frequency $\nu_m = (\omega_c\omega_D)^{1/2}/2\pi = 1$ GHz has the value 3.75 dB cm^{-1}. This is in very good agreement with the recent measurements of King and Rosenberg [5], who measured the temperature dependence of the attenuation of a fast transverse wave parallel to the $\langle 110 \rangle$ direction and of the frequency of 1.02 GHz in the range of 20—50 °K. Their sample had at 77 °K the electron concentration 6×10^{23} m^{-3} and the mobility 9 m^2/V s. By extrapolation of their experimental dependence to 77 °K we obtain $\alpha_L \doteq 4.5$ dB cm^{-1}. Thus we see that the value of the ratio α_L/α_0 which we have used is resonable.

Concluding we can say that using the White formula for the amplification of acoustic waves and formula (2) for the mobility we succeeded to explain the observed dependence of the current decrease, which we identified as an acoustoelectric current, on the magnetic field after the acoustoelectric domain formation in the range of not too large electric and magnetic fields. Since the current density decrease Δi as well as the current density i are relatively well measurable quantities, we can determine well from the dependence of Δi on B the ratio α_L/α_0, if the concentration of electrons and their mobility is known. If also the absorption α_L is known we can determine the electromechanical coupling constant K^2 and thus also the piezoelectric constant, which is difficult to measure in InSb directly.

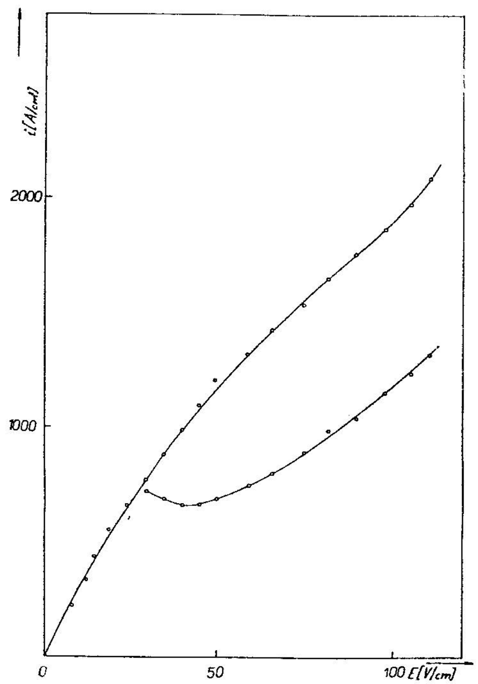

Fig. 4. Current density as a function of the applied electric fi ld in the case $B = 0$.

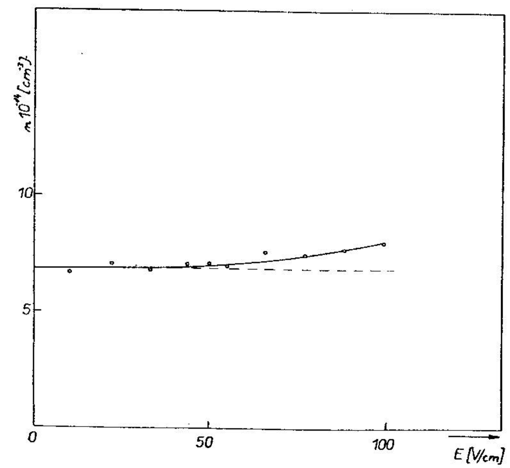

Fig. 5. Electron concentration as a function of the applied electric field.

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Received November 10th, 1970